Theoretical and experimental analysis of glazed serpentine tube flat plate collector for effluent evaporation

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Abstract: In this paper theoretical and experimental study of serpentine tube flat plate collector for evaporation of water in the effluent is presented. The performance of the flat plate collector depends on various factors including the collector construction and the arrangement of the system. The prototype working model has been fabricated to prove the feasibility and viability of the evaporation system. Results obtained show that the evaporation rate of water in the effluent increases, with the increase in solar radiation, wind velocity and decrease in mass flow rate of effluent, relative humidity and concentration of the effluent. The evaporation rate of effluent in the single cover serpentine tube flat plate collector is found to increase by 41 % compared to the solar pan and 16% to the single cover FRP flat plate collector.

Keywords: solar energy; effluent; evaporation; glazing; serpentine tube flat plate collector.

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1 Introduction

The minimisation of water in the effluent is an objective of an industrial effluent treatment, and the evaporation is most important operation in the effluent treatment. Various evaporating methods are employed but these methods are based on the conventional electrical energy and needs many electrical appliances like pumps, agitators and electrical heaters. But all these auxiliaries consume extra electrical power, to overcome this extra electrical power, it is necessary to use natural resources like solar energy. The soak liquor contains large amount of chlorides and total dissolved solids (TDS), which affects the biological oxygen demand (BOD), chemical oxygen demand (COD) and P_H value of water. As far as concern with the TDS in the effluent, tanneries are required by the pollution control authority to separate the waste streams from soak liquor. The salt concentration in the effluent is 3.5% to 6 %. The conventional method is not suitable for high TDS effluent, and this issue is especially noticeable in developing countries where mixing of tannery effluent with domestic waste water. Due to high transportation cost the discharge of high TDS effluent into the sea is not reasonable, and relocates the tanneries to the seaside is also not feasible. The distillate come from the treated effluent by reverse osmosis is very extortionate (Mani et al., 1999). This large quantity of such highly saline effluent is discharged while processing of one tone of wet salted raw stock. Based on the average rate of evaporation of effluent from the surface of pan is taken as 4.5 mm per day. On the basis of this rate of evaporation the pollution control authority has recommend 222 m^2 area of solar pan for evaporation of 1,000 litres of saline effluent per day (Mani et al., 1999). Sritar and Mani (2004) worked on the single cover FRP flat plate collector and found that the evaporation rate increases by 2.2 to 3.2 times as compare to the conventional shallow solar pans, which will minimise the area about 29%. There for area required for single cover FRP flat plate collector is 157 m^2 for evaporation of 1,000 litres of effluent per day.

In the natural ponds some of the effluent evaporates but most of the effluent percolates and pollute ground water sources as well as soil. The cost of land and availability of the land at the campus is another major issue. In the present work experimental studies to increase the evaporation rate, in an improved system, have been carried out in a single cover serpentine tube flat plate collector. Based on this the effectiveness of operational and meteorological parameters on the evaporation rate of saline effluent in the improved system has been analysed. It is an accepted fact that the rate of evaporation in conventional solar pans is influenced by temperature of effluent, area of contact between the surface of effluent and air, atmospheric temperature, intensity of solar radiation, relative humidity and wind velocity. The evaporation rate of effluent can be accelerating by any one or a combination of the following methods (Mani et al., 1999).

1 Increasing the temperature of the effluent.
2 Increasing the contact area between the surface of effluent and air.
3 Increasing the atmospheric air temperature.
4 Decreasing the humidity of air.
5 Increasing the wind velocity flowing over the effluent surface.

The last three methods are very complicated to installation, and that requires high operational cost. While the first two methods are simple and easy to implement for increasing the temperature of effluent and contact area between the surface of effluent and air (Kakabadev and Golaev, 1971; Yang and Pai-Lu, 2001; Gandhidasan, 1983; Mani and Srinivasa Murty, 1993; Jacov et al., 2001; Mani and Sritar, 2001). In view of this single cover serpentine tube flat plate collector is used for increasing the temperature of effluent and contact area between the effluent and air. Schematic of the single cover serpentine tube flat plate collector is shown in Figure 1.

2 Theoretical analysis

The equations governing the energy balance for the single cover serpentine tube flat plate collector is obtained from (Gandhidasan, 1983; Mani and Srinivasa Murty, 1993; Gandhidasan, 1995; Collier, 1979) energy absorbed by the serpentine tube flat plate collector and the summation of energy lost by conduction (E_{con}), Convection (E_{conv}), radiation (E_{rad}) and energy utilised for evaporation (E_{evp}) and energy gained by solution (E_{sol}).

$$I_\beta \alpha \tau A_c dt = E_{con} + E_{conv} + E_{rad} + E_{evp} + E_{sol} \tag{1}$$

The solar radiation falling on an inclined surface is evaluated by using (Sritar and Mani, 2004)

$$I_\beta = \left(I_g - I_d\right)\left(\frac{\cos\theta_i}{\cos\theta_z}\right) + \frac{I_d(1+\cos\beta)}{2} \tag{2}$$

where

θ_i is the angle of incidence on an inclined surface.

θ_z is the angle of incidence on a horizontal surface.

Incidence angles are given by (Tiwari, 2013)

$$\cos\theta_i = [\cos(\emptyset - \beta)\cos\delta\cos h + \sin(\emptyset - \beta)\sin\delta] \tag{3}$$

$$\cos\theta_z \text{ c}[\cos\emptyset\cos\delta\cos h + \sin\emptyset\sin\delta] \tag{4}$$

The Absorptivity (α) of the black coated copper collector is taken as 0.95 and Transmissivity (τ) of the glass cover is 0.90

The energy loss due to heat conduction through the base and side of the collector is evaluated by (Tiwari, 2013)

$$E_{con} = U_b + U_s \tag{5}$$

$$U_b = \left[\frac{L_{in}}{K_{in}} + \frac{1}{h_b}\right]^{-1} \tag{6}$$

Consider the energy lost from the side insulation of the collector is exactly the same as that from the base because the thickness of the side insulation is the same as that of the base insulation (Tiwari, 2013)

$$U_s = U_b \left(\frac{A_s}{A_c} \right) \tag{7}$$

The energy lost by convection is evaluated by

$$h_c = h_{c_1} + h_{c_2}$$

The convective heat loss between plate and cover is evaluated by (Tiwari, 2013)

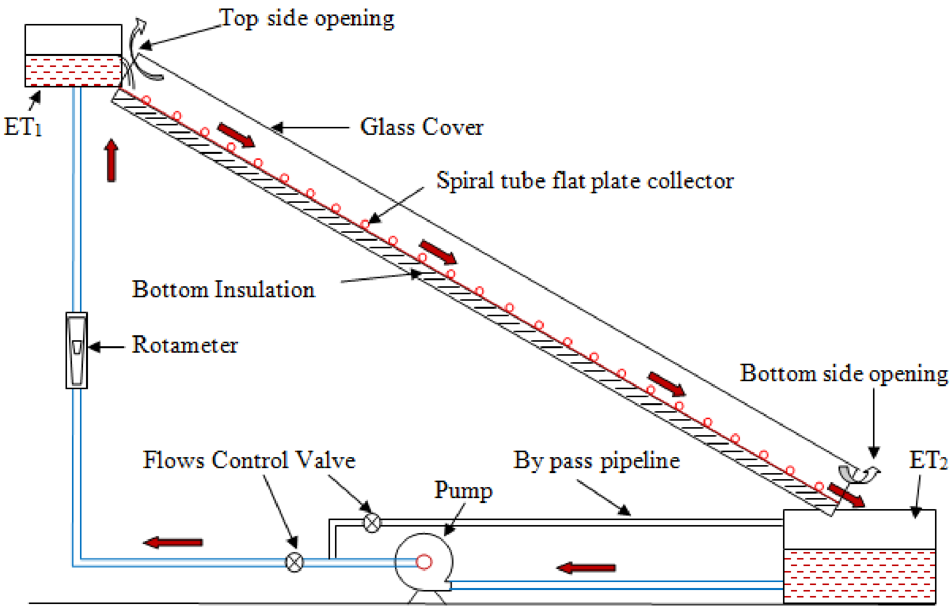
$$h_{c_1} = \frac{N_u K}{L} \tag{8}$$

The value of Nusselt number for air between the absorber plate and the glass cover is obtained by using the equation given by and Tiwari (2013).

$$N_u = 1 + 1 \cdot 44 \left[1 - \frac{1,708}{R_a \cos\beta} \right] \left(1 - \frac{\sin(1 \cdot 8\beta)^{1 \cdot 6} 1,708}{R_a \cos\beta} \right) + \left[\left(\frac{R_a \cos\beta}{5,830} \right)^3 - 1 \right] \tag{9}$$

where $R_a = \dfrac{g\beta' \Delta T L^3}{\nu\alpha}$.

Figure 1 Schematic diagram of single cover serpentine tube flat plate collector (see online version for colours)



The convective heat loss coefficient from the top surface of glazing to the atmosphere is given by Tiwari (2013), $h_{c_2} = 2 \cdot 8 + 3 \cdot 0$ W, where W is the wind velocity over the top glass cover.

The energy lost due to radiation is calculated by

$$E_{rad} = E_{r_1} + E_{r_2} + E_{r_3} \tag{10}$$

The amount of Radiative heat loss from the absorber plate to glass cover is calculated by (Tiwari, 2013)

$$E_{r_1} = \varepsilon_{eff}\sigma \frac{\left[(T_p + 273)^4 - (T_g + 273)^4\right]}{T_p - T_g} \tag{11}$$

where $\varepsilon_{eff} = \left[\frac{1}{\varepsilon_p} + \frac{1}{\varepsilon_g} - 1\right]^{-1}$ and $\sigma = 5.67 \times 10^{-8}$ W/m^{2}K^4.

The amount of Radiative heat loss from glass cover to the atmosphere is calculated by (Tiwari, 2013)

$$E_{r_2} = \varepsilon_g \sigma \frac{\left[(T_g + 273)^4 - (T_{sol} + 273)^4\right]}{T_g - T_{atm}} \tag{12}$$

where $T_{atm} = T_{sky} + 6$ (Sukhatme and Nayak, 2007)

The amount of Radiative heat loss from the solution is calculated by (Sritar and Mani, 2004)

$$E_{r_3} = \sigma \left[\frac{1}{\varepsilon_3} + \frac{1}{\varepsilon_g} - 1\right]^{-1} A\left(T_{sol}^4 - T_g^4\right)dt \tag{13}$$

The energy required for evaporation of water from the effluent is calculated from (Sritar and Mani, 2004)

$$E_{evp} = \beta_m A\left(P_{par,sol} - P_{par,w}\right) h_{fg} dt \tag{14}$$

The psychrometric ratio as per Dropkin's measurement is given by (Gandhidasan, 1983)

$$\frac{h_c}{\beta_k} = 950\text{Jkg}^{-1}\text{K}^{-1} \tag{15}$$

where $\beta_m = \frac{0.622\beta_k}{P}$ (Gandhidasan, 1983).

The vapour pressure of water in the solution is calculated from (Mani and Srinivasa Murty, 1993)

$$P_{par,sol} = P_w(1 - 0.000537S) \tag{16}$$

Energy gained by the solution is evaluated from (Sukhatme and Nayak, 2007)

$$E_{sol} = m_f C_p \Delta T_{sol} \tag{17}$$

The specific heat of the solution, is calculated from (Mani and Srinivasa Murty, 1993)

$$C_p = C_1 + C_2 T_{sol} + C_3 T_{sol}^2 + C_4 T_{sol}^3 \tag{18}$$

The constants are C_1, C_2, C_3 and C_4 calculated from

$$C_1 = 4,206.8 - 6.6197S + 1.2288\times10^{-2}S^2$$
$$C_2 = -1.1262 + 5.4178\times10^{-2}S - 2.2719\times10^{-4}S^2$$
$$C_3 = 1.2026\times10^{-2} - 5.5366\times10^{4}S + 1.8906\times10^{-6}S^2$$
$$C_4 = 6.8774\times10^{-7} + 1.517\times10^{-6}S - 4.4268\times10^{-9}S^2$$

Collector efficiency factor for serpentine tube flat plate is the ratio of rate of actual useful thermal energy collection to the rate of useful thermal energy collection when the absorber of the collector is at the local fluid temperature (Tiwari et al., 2016).

Rate of actual useful thermal energy gain by the effluent from the absorber plate can be obtained by

$$Q_u = \dot{m}_f C_p (\Delta T) \tag{19}$$

Rate of useful thermal energy collection when the absorber of the collector is at the local fluid temperature

$$Q_u = \dot{F}A_c\left[\alpha\tau I - U_L\left(T_{fl} - T_{atm}\right)\right] \tag{20}$$

The collector efficiency factor can be obtained by equating equations (19) and (20)

$$\dot{F} = \frac{\dot{m}_f C_f (\Delta T)}{\alpha\tau I - U_L\left(T_{fl} - T_{atm}\right)A_c} \tag{21}$$

Equation (20) is valid for

$$\alpha\tau I - U_L\left(T_{fl} - T_{atm}\right) > 0 \text{ and } T_{fl} > T_{atm}$$
$$I^{th} > \frac{U_L\left(T_{fl} - T_{atm}\right)}{\alpha\tau}$$
$$I^{th} \rightarrow \text{ threshold condition for operation of system}$$

Heat removal factor of serpentine collector is the ratio of the rate of actual useful thermal energy gain to the rate of useful thermal energy gain of the entire flat plate collector were the mass flow rate of effluent is high

$$Q_u = \dot{m}_f C_f\left(T_{out} - T_{in}\right) \tag{22}$$

$$Q_u = F_R\left[\alpha\tau I(t) - U_L\left(T_{in} - T_a\right)\right]A_c \text{ where } T_{in} > T_a \tag{23}$$

The collector thermal energy removal factor can be obtained by equating equation (22) and (23)

$$F_R = \frac{\dot{m}_f C_f\left(T_{out} - T_{in}\right)}{\left[\alpha\tau I(t) - U_L\left(T_{in} - T_a\right)\right]A_c} \tag{24}$$

The mass of water evaporation with time interval is calculated by

$$M_{w,evp} = \beta_m A\left(P_{par,sol} - P_{par,w}\right)dt \tag{25}$$

For next time interval, the parameters are delimitate as

$$T_{sol} = T_{sol} + \Delta T_{sol} \tag{26}$$

$$M_w = M_w - M_{w,evp} \tag{27}$$

Repeat this procedure throughout the day of the experimentation.

Thermal efficiency of the serpentine tube flat plate collector. The thermal performance of a collector is expressed by its thermal efficiency that is usually the ratio of the systems thermal energy utilisation to the solar radiation incident on the collector.

$$\eta^{th} = \frac{Q_u}{I_\beta \alpha \tau A_c} \tag{28}$$

The calculations are carried out by using an initial value of effluent temperature. Consider an initial effluent temperature is equal to the atmospheric temperature, assumed the time interval, *dt* is as 5 seconds. For this condition, the glazing cover temperature and the increase in effluent temperature during the same time interval is calculated by solving equations (10), (11), (12) and (1). For calculating ΔT_{sol} theoretically, the experimentally measured values of wind speed, solar radiation, atmospheric temperature and relative humidity of the particular day and hour were used.

3 Experimental set-up and observations

Figure 2 shows the photograph of experimental set-up, black paint coated copper thin sheet of 2 m * 1 m is used as absorber of flat plate collector. The copper tube is bonded to the absorber plate in a serpentine fashion. The spacing between the absorber plate and top glass cover is 0.1 m to intercept the condensation of water vapours at the bottom side of the glass cover. The bottom and top side walls of the serpentine tube flat plate collector are open to permit to escape the water vapours in to the atmosphere, as shown in Figure 1. There are two tanks the over head tank (ET_1) and effluent storage tank (ET_2). Over head tank is a perforated for constant flow of effluent over flat plate collector. Effluent is pumped from effluent tank to over head tank and distributes it on the absorber plate. The mass flow rate of effluent flowing between the glass cover and the absorber of flat plate collector is measured by using rotameter which is situated at the header pipe. The excess effluent flows back to effluent storage tank through bypass pipe line to maintain constant head in the over head tank. The effluent is collected at the lower side of the flat plate collector which rests on the effluent storage tank. The effluent is re-circulated from storage tank to over head tank and the cycle is repeated.

The quantity of water in the effluent evaporated throughout one hour is measured by using calibrated scale on the effluent tank. The amount of water which is evaporated from effluent is added by fresh water for maintaining the concentration of the effluent. The effluent temperature at the entry and exit are measured by using RTD and recorded in the data logger. Dry and wet bulb temperatures are measured by using mercury thermometers for relative humidity calculation. The solar radiation is measured by using SEAWARD irradiance metre. The concentration of the effluent is measured by using specific gravity metre. The experimentation was carried out from 9 am to 17 pm each day. The measurement of parameters such as mass flow rate of effluent, effluent temperature, atmospheric temperature, wind speed and wet and dry bulb temperatures were recorded every one minute's basis. The accuracies measuring ranges of the instruments are as shown in Table 1.

Figure 2 Experimental test setup of serpentine tube flat plate collector (see online version for colours)

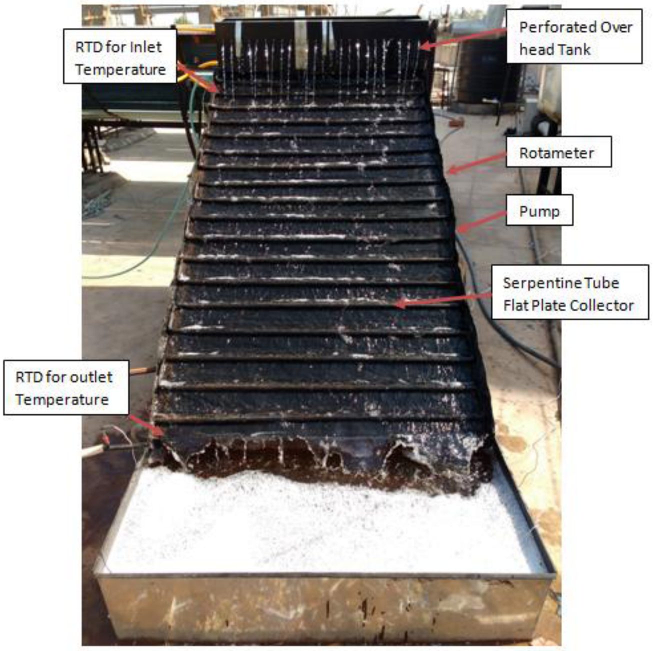


Table 1 Accuracies, measuring ranges and uncertainty of instruments

Sr. no.	*Instrument*	*Operating range*	*Accuracy*	*Uncertainty*
01	SEAWARD Pyranometer	0 – 2,000 w/m^2	± 0.05 w/m^2	0.57%
02	RTD	0 – 1,400°C	± 0.5°C	0.18%
03	Mercury Thermometer	0 °C to 120 °C	± 0.5°C	0.12%
04	Wet and dry bulb thermometer	–10 °C to 50 °C	± 0.5°C	0.12%
05	Digital anemometer	0 – 100 m/s	± 0.1 m/s	0.18%

4 Results and discussion

The evaporation rate of effluent depends on the parameters such as mass flow rate, concentration of effluent, solar radiation, relative humidity and wind velocity.

4.1 *Effect of mass flow rate on evaporation rate*

The mass flow rate has important influence on the solar system. From theoretical and experimental analysis it is observed that maximum evaporation is achieved for mass flow rate of 200 l/h. Maximum evaporation takes place during 1 to 2 pm. The flow rate of 500 l/h yields less evaporation rate compared to 200 l/ h. Figure 3 depicts the effect of mass flow rate of effluent on the evaporation rate. In theoretical analysis deviation of 7% is observed.

Figure 3 Effect of mass flow rate on evaporation rate (see online version for colours)

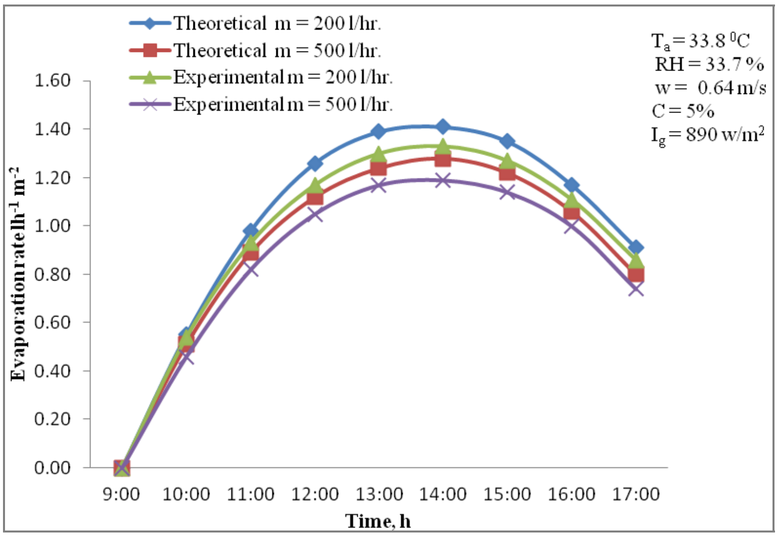
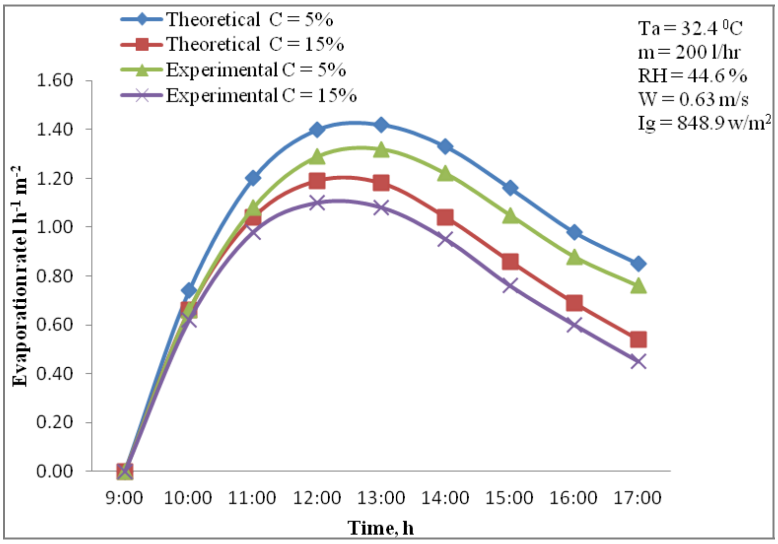


Figure 4 Effect of concentration on evaporation rate (see online version for colours)



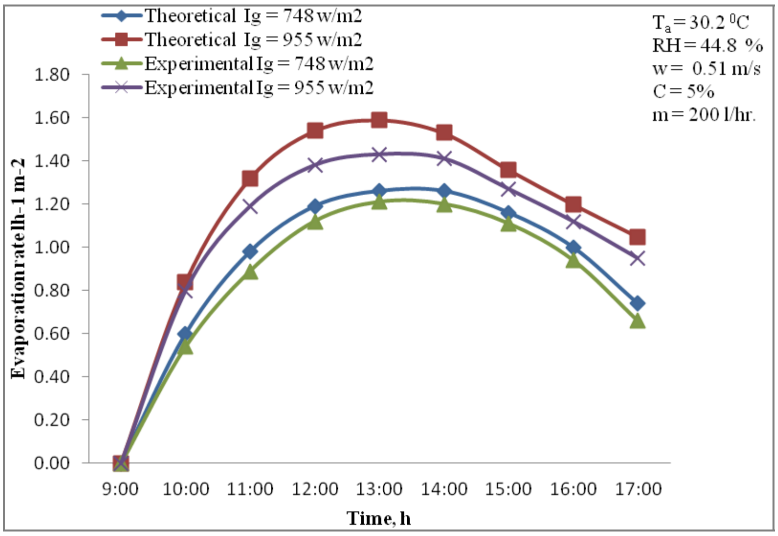
4.2 *Effect of concentration on evaporation rate*

As the water in the effluent evaporates, the concentration of the effluent increases and that reduces the partial pressure of water in the effluent. The partial pressure of water in the effluent decreases the humidity difference between the surface of the effluent and the atmospheric air. From experimental analysis it is observed that maximum evaporation is achieved for concentration of 5%. As the concentration of effluent increases, the evaporation rate of water decreases. Figure 4 exhibits the effect of concentration on the evaporation rate. The deviation of the experimental performance is 9% as that of the theoretical value.

4.3 *Effect of solar insolation on evaporation rate*

As the intensity of solar radiation increases the effluent temperature also increases. The increase in effluent temperature increases the partial pressure between the effluent and the atmospheric air, and that increases the evaporation rate. Figure 5 shows the effect of solar radiation on evaporation rate. Experimental performance deviates 8% as compared to that hypothetical analysis.

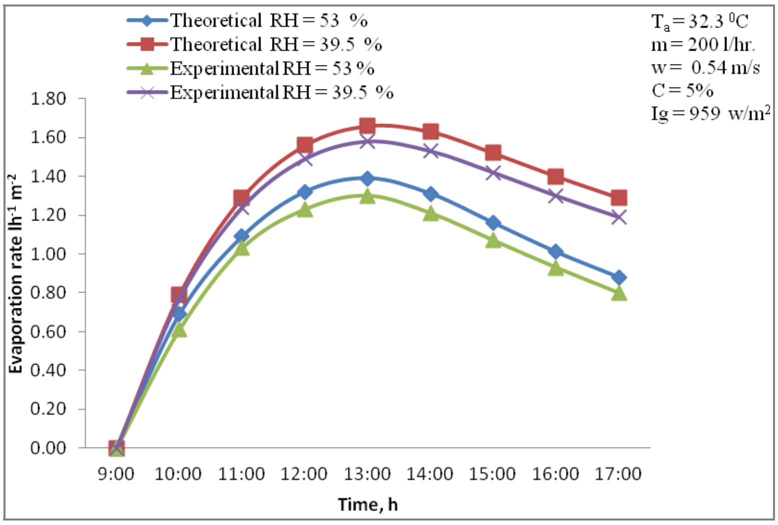
Figure 5 Effect of solar insolation on evaporation rate (see online version for colours)



4.4 *Effect of relative humidity on evaporation rate*

Partial pressure between the effluent and the atmospheric air also depends on the relative humidity. As the relative humidity increases the partial pressure difference between the effluent and the atmospheric air decreases and this decreases the evaporation rate. This can be seen in Figure 6. The deviation between the experimentation and hypothetical analysis is observed as 7%.

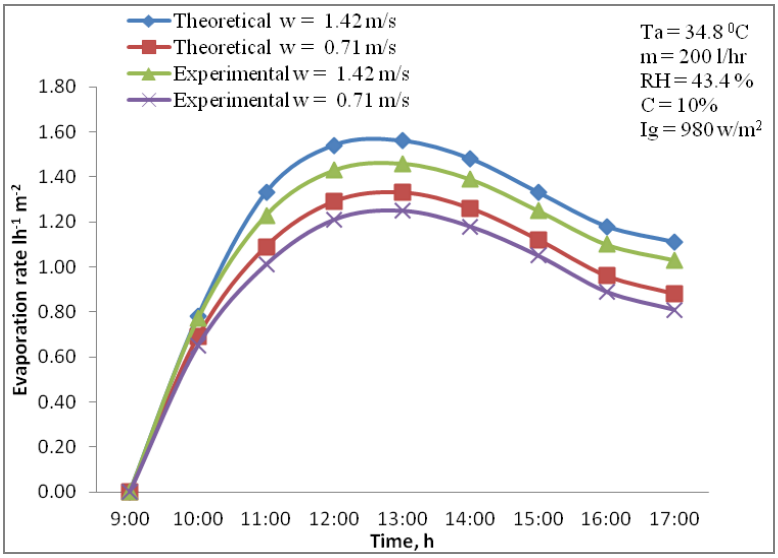
Figure 6 Effect of relative humidity on evaporation rate (see online version for colours)



4.5 *Effect of wind speed on evaporation rate*

As the wind velocity increases, more quantity of air comes in contact with the surface of the effluent, which accelerates the mass transfer rate. This results in increase in evaporation rate of water in the effluent. Figure 7 shows the effect of wind speed on evaporation rate. The experimental results deviates 7% from the hypothetical analysis.

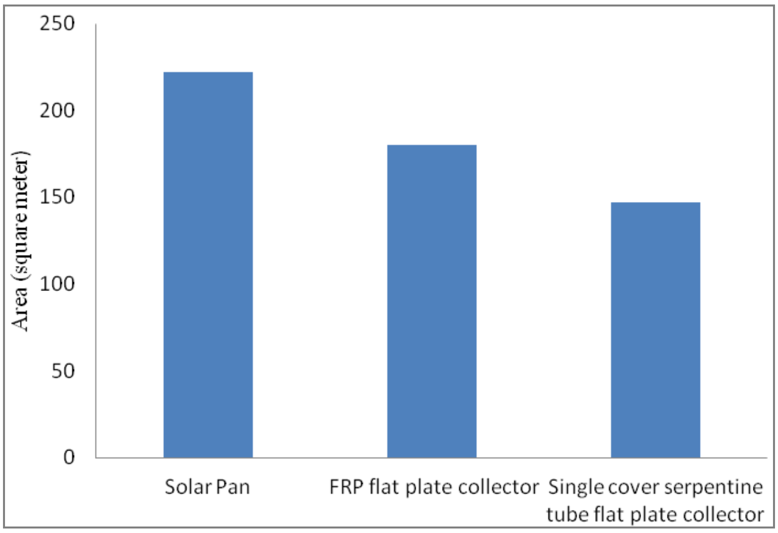
Figure 7 Effect of wind speed on evaporation rate (see online version for colours)



4.6 Comparison of area required for solar pan, single cover FRP flat plate collector and single cover serpentine tube flat plate collector

Figure 8 shows that the single cover serpentine tube flat plate collector requires 41% less area as compared to solar pan and 16% less compared to single cover FRP flat plate collector for the same evaporation of effluent.

Figure 8 Area required for 1,000 litre of effluent evaporation (see online version for colours)



5 Conclusions

In the present work theoretical and experimental analysis of single cover serpentine tube flat plate collector for effluent evaporation is carried out. From the theoretical and experimental analysis, following conclusions are drawn.

1 From the theoretical and experimental results, evaporation rate of water increases, with increase in solar radiation, wind velocity and increases with decrease in mass flow rate of effluent, concentration and relative humidity.

2 A comparison between the theoretical and experimental quantification show they agree to within 9%.

3 Single cover serpentine tube flat plate collector requires less area as compared to single cover FRP flat plate collector and solar pan for the same evaporation of effluent.

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Nomenclature

A_c	area of collector
C	concentration of the effluent
C_p	specific heat of the effluent
dt	time interval
E_{conv}	convective energy lost
E_{evp}	energy utilised for water evaporation from the effluent
E_{con}	energy lost by conduction
E_{rad}	energy lost by radiation
E_{sol}	energy gain by the solution
ET_1	constant head perforated effluent tank
ET_2	calibrated effluent storage tank
FRP	fiber reinforced plastic
g	gravitational force

G_r	Grashof number
h_b	bottom loss coefficient
h_c	convective heat transfer coefficient between the effluent and atmospheric air
h_{fg}	latent heat of vaporisation from the solution
I_d	diffuse solar radiation on a horizontal plane
I_g	global radiation on a horizontal plane
I_β	solar radiation on an inclined surface
K	thermal conductivity of air
K_{in}	thermal conductivity of insulation
L_{in}	thickness of the insulation
L_c	characteristic length
L	distance between glass cover to the absorber plate
$\dot{m}_f$	total mass flow rate of effluent on the absorber plate
M_w	mass of water
$M_{w,evp}$	evaporated mass of water from the effluent
P	atmospheric pressure
Pr	Prandtl number
P_1	pump for effluent flow
$P_{par,sol}$	Partial pressure of the solution
$P_{par,w}$	partial pressure of water vapour in the atmospheric air
P_W	saturation pressure of water vapour in the effluent at Ts
Re	Reynolds number
RH	relative humidity
T_{atm}	atmospheric temperature
T_{eff}	effective sky temperature
T_{fl}	Local fluid temperature
T_g	top glass cover temperature
T_{in}	inlet effluent temperature
T_{out}	outlet effluent temperature
T_p	absorber plate temperature
T_{sol}	solution temperature
U_L	overall heat loss coefficient
U_b	heat conduction through the base of the collector
Us	heat conduction through the side of the collector
W	wind speed
ΔT_{sol}	rise in temperature of the solution
Δ_X	thickness of the absorber plate
α	absorptivity of absorber
τ	transmissivity of glass cover
ϕ	latitude of a location

δ	declination angle
ω	hour angle
β	collector surface inclination
β_c	$1/T_f$ = expansion coefficient
β_k	mass transfer coefficient with humidity ratio as the driving force
β_m	mass transfer coefficient with vapour pressure as the driving force
σ	Stefan- Boltzmann constant
ε_g	glass cover emissivity
ε_p	absorber plate emissivity
ε_{eff}	effective emissivity of plate glazing system